

E1 transitions between states with $n=1$ to 6 in helium-like carbon, nitrogen, oxygen, neon, silicon, and argon

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ABSTRACT

Wavelengths and transition rates are given for E1 transitions between singlet 1S , 1P , 1D , and 1F states, between triplet 3S , 3P , and 3D states, and between triplet 3P_1 and singlet 1S_0 states in ions of astrophysical interest: helium-like carbon, nitrogen, oxygen, neon, silicon, and argon. All possible E1 transitions between states with $J \leq 3$ and $n \leq 6$ are considered. Energy levels and wave functions used in calculations of the transition rates are obtained from relativistic configuration-interaction calculations that include both Coulomb and Breit interactions.

Subject headings: physical data and processes: atomic data, plasmas

1. Introduction

The emission lines resulting from electron capture by multicharged ions colliding with neutral gases provide a powerful diagnostic probe of astrophysical plasmas. X-rays seen in auroras on Jupiter (Metzger et al. 1983; Waite et al. 1994; Cravens et al. 1995; Kharchenko et al. 1998), in comets (Lisse et al. 1996; Dennerl et al. 1997; Weaver et al. 2001) and the X-ray background (Cravens 2000; Cravens et al. 2001) have been attributed to electron capture by heavy ions.

Several laboratory studies of the X-ray emissions have been carried out (Greenwood et al. 2000; Beiersdorfer et al. 2000; Lubinski et al. 2001; Greenwood et al. 2001; Beiersdorfer et al. 2001; Ma et al. 2001; Flechard et al. 2001; Hasan et al. 2001). The interpretation of the laboratory data and the astrophysical data requires a reliable description of the radiative cascade that follows the capture into excited states.

The cascade lines appearing at extreme ultra-

violet wavelengths provide additional probes of the environments in which the multicharged heavy ions are present. For the helium-like ions interesting differences may occur as the nuclear charge of the ions changes. It has long been known that for ions beyond N^{5+} the spin-forbidden $2^3P_1 - 1^1S_0$ transition is more probable than the allowed $2^3P_1 - 2^3S_1$ transition (Drake & Dalgarno 1969).

In the most recent National Institute of Standards and Technology (NIST) data compilation (Wiese et al. 1996), recommended transition rates for helium-like C, N, and O are based primarily on nonrelativistic calculations by Cann & Thakkar (1992), who used explicitly correlated wave functions for singlet and triplet S , P , and D states with $n \leq 6$ to calculate energies and dipole oscillator strengths for $S - P$ and $P - D$ transitions in helium-like ions with Z from 2 to 10.

In this paper, we extend the results of previous calculations using relativistic configuration-interaction (CI) wave functions and energies for $(1snl)^{2S+1}L_J$ states of helium-like ions with $J \leq$

3, $n \leq 6$, and $Z = 6, 7, 8, 10, 14$, and 18. We present results here for the allowed singlet-singlet and triplet-triplet transitions. The rates for triplet-triplet transitions are determined by averaging the calculated rates over fine-structure substates. Additionally, we present data for intercombination transitions between 3P_1 and 1S_0 states.

Relativistic CI calculations of wavelengths and transition probabilities have been carried out previously for E1, M1, and M2 transitions between $n = 1$ and 2 states of helium-like ions (Plante et al. 1995). Nonrelativistic many-body perturbation theory, treating relativistic corrections perturbatively, has also been used to calculate energies of $(1snl)$ states with $n = 2-5$ and $l = 0-2$ (Vainshtein & Safronova 1985). The present calculations extend previous relativistic calculations to $n > 2$ and extend previous nonrelativistic calculations to higher values of Z .

The importance of accurate atomic characteristics for astrophysics was further illustrated by Kharchenko & Dalgarno (2001), where the variability of cometary X-ray emission induced by solar wind ions was studied.

2. Calculation

Relativistic CI calculations were introduced to evaluate precise values of energies of $n = 1$ and 2 states of helium-like ions (Chen et al. 1993; Cheng et al. 1994) and used subsequently to evaluate transition energies and transition rates between states of helium-like ions with $n = 1$ and 2 (Plante et al. 1995). In the present paper, we apply the methods developed in these earlier papers to evaluate wavelengths and rates for E1 transitions between $(1snl)$ states with $n \leq 6$ in various helium-like ions of astrophysical interest. The computational method is summarized in the following paragraphs.

2.1. Wave Functions and Energies

The wave function describing a state with angular momentum J, M in a two-electron ion may be written as

$$\Psi_{JM} = \sum_{i \leq j} c_{ij} \Phi_{ij}(JM), \quad (1)$$

where the quantities c_{ij} are expansion coefficients and where $\Phi_{ij}(JM)$, the configuration state vectors, are given by

$$\Phi_{ij}(JM) = \eta_{ij} \sum_{m_i m_j} \langle j_i m_i, j_j m_j | JM \rangle a_i^\dagger a_j^\dagger | 0 \rangle, \quad (2)$$

in second quantization, with

$$\eta_{ij} = \begin{cases} 1, & i \neq j, \\ 1/\sqrt{2}, & i = j. \end{cases} \quad (3)$$

In the above equations, we use subscripts i to designate quantum numbers (n_i, j_i, l_i, m_i) of one-electron states. The quantities c_{ij} , $\Phi_{ij}(JM)$, and η_{ij} are independent of magnetic quantum numbers m_i and m_j . To construct a state of even or odd parity, one requires the sum of orbital angular momenta $l_i + l_j$ to be either even or odd, respectively. From the symmetry properties of the Clebsch-Gordan coefficients, it can be shown that

$$\Phi_{ij}(JM) = (-1)^{j_i + j_j + J + 1} \Phi_{ji}(JM). \quad (4)$$

This relation, in turn, implies that $\Phi_{ii}(JM)$ vanishes unless J is even. The wave-function normalization condition has the form

$$\langle \Psi_{JM} | \Psi_{JM} \rangle = \sum_{i \leq j} c_{ij}^2 = 1. \quad (5)$$

Substituting Ψ_{JM} into the Schrödinger equation $(H_0 + V)\Psi_{JM} = E\Psi_{JM}$, one obtains the following set of linear equations for the expansion coefficients c_{ij} :

$$(\epsilon_i + \epsilon_j)c_{ij} + \sum_{k \leq l} \eta_{ij} V_J(ij; kl) \eta_{kl} c_{kl} = E c_{ij}. \quad (6)$$

The potential matrix in Eq. (6) is

$$\begin{aligned} V_J(ij; kl) = & \sum_L (-1)^{j_j + j_k + L + J} \begin{Bmatrix} j_i & j_j & J \\ j_l & j_k & L \end{Bmatrix} X_L(ijkl) \\ & + \sum_L (-1)^{j_j + j_k + L} \begin{Bmatrix} j_i & j_j & J \\ j_k & j_l & L \end{Bmatrix} X_L(ijlk), \end{aligned} \quad (7)$$

where the quantities $X_L(ijkl)$ are given by

$$X_L(ijkl) = (-1)^L \langle \kappa_i || C_L || \kappa_k \rangle \langle \kappa_j || C_L || \kappa_l \rangle R_L(ijkl). \quad (8)$$

The coefficients $\langle \kappa_i || C_L || \kappa_j \rangle$ in the above equation are reduced matrix elements of normalized spherical harmonics, and the quantities $R_L(ijkl)$ are relativistic Slater integrals (Chen et al. 1993; Plante et al. 1994). In the present calculation, where both the Coulomb and Breit interactions are included in the Hamiltonian,

$$X_L(ijkl) \rightarrow X_L(ijkl) + M_L(ijkl) + N_L(ijkl) + O_L(ijkl), \quad (9)$$

where $M_L(ijkl)$, $N_L(ijkl)$, and $O_L(ijkl)$ are magnetic Slater integrals (Johnson et al. 1988).

Identification of the levels obtained by solving the CI equations was aided by comparison with the online NIST database (2001).

2.2. Transition Amplitudes and Rates

Using the CI wave functions discussed in Sec. 2.1 for both the initial and final states and carrying out the sums over magnetic substates, one obtains the following expression for the reduced electric-dipole matrix element

$$\begin{aligned} \langle F || D || I \rangle = & -\sqrt{[J_I][J_F]} \sum_{\substack{m \leq n \\ r \leq s}} \eta_{rs} \eta_{mn} c_{rs}^{(F)} c_{mn}^{(I)} \times \\ & \left\{ (-1)^{j_r+j_s+J_I} \begin{Bmatrix} 1 & J_I & J_F \\ j_s & j_r & j_m \end{Bmatrix} \langle r || d || m \rangle \delta_{ns} \right. \\ & + (-1)^{j_r+j_n} \begin{Bmatrix} 1 & J_I & J_F \\ j_s & j_r & j_n \end{Bmatrix} \langle r || d || n \rangle \delta_{ms} \\ & + (-1)^{J_F+J_I+1} \begin{Bmatrix} 1 & J_I & J_F \\ j_r & j_s & j_m \end{Bmatrix} \langle s || d || m \rangle \delta_{nr} \\ & \left. + (-1)^{j_r+j_n+J_F} \begin{Bmatrix} 1 & J_I & J_F \\ j_r & j_s & j_n \end{Bmatrix} \langle s || d || n \rangle \delta_{mr} \right\}, \quad (10) \end{aligned}$$

where $[J] = 2J + 1$. The one-electron reduced matrix elements $\langle m || d || n \rangle$ in Eq. (10) are given by

$$\begin{aligned} \langle \kappa_i || d || \kappa_j \rangle = & \frac{3}{k} \langle \kappa_i || C_1 || \kappa_j \rangle \\ & \int_0^\infty dr \left\{ j_1(kr) [P_i(r)P_j(r) + Q_i(r)Q_j(r)] \right. \\ & + j_2(kr) \left[\frac{\kappa_i - \kappa_j}{2} [P_i(r)Q_j(r) + Q_i(r)P_j(r)] \right. \\ & \left. \left. + [P_i(r)Q_j(r) - Q_i(r)P_j(r)] \right] \right\}, \quad (11) \end{aligned}$$

in length form, and

$$\begin{aligned} \langle \kappa_i || d || \kappa_j \rangle = & \frac{3}{k} \langle \kappa_i || C_1 || \kappa_j \rangle \\ & \int_0^\infty dr \left\{ -\frac{\kappa_i - \kappa_j}{2} \left[\frac{dj_1(kr)}{dkr} + \frac{j_1(kr)}{kr} \right] \times \right. \\ & [P_i(r)Q_j(r) + Q_i(r)P_j(r)] \\ & \left. + \frac{j_1(kr)}{kr} [P_i(r)Q_j(r) - Q_i(r)P_j(r)] \right\}, \quad (12) \end{aligned}$$

in velocity form. In Eqs. (11) and (12), the quantities $P_i(r)$ and $Q_i(r)$ are large- and small-component radial Dirac wave functions for state i and $j_l(kr)$ is a spherical Bessel function of order l ; $k = 2\pi/\lambda$ being the magnitude of the wave vector. These dipole matrix elements are fully retarded. The dipole transition rates are given in terms of the dipole matrix elements by

$$A_{FI} = \frac{2.0613 \times 10^{18}}{[J_F]\lambda^3} S_{FI}, \quad (13)$$

where $S_{FI} = |\langle F || D || I \rangle|^2$ is the line-strength of the transition (atomic units) and λ is the transition wavelength (Å).

3. Discussion of Tables

We solve the CI-equation (6) using the method described in Chen et al. (1993) to obtain wave functions for $(1snl)^{2S+1}L_J$ states with $J \leq 3$, $S = 0$ & 1, and $n \leq 6$ for helium-like ions with $Z = 6, 7, 8, 10, 14$, and 18. The energies obtained from the CI calculations are in precise agreement with earlier relativistic calculations (Plante et al. 1994) and in agreement to parts in 10^4 with the nonrelativistic CI calculations of Cann & Thakkar (1992). The wavelengths for transitions between nearly degenerate levels are less accurate than the level energies owing to cancellation. The present wavelengths agree with NIST tabulations of measured wavelengths (Wiese et al. 1996) to better than 0.02% for $\lambda < 200$ Å, to better than 0.2% for $200 \leq \lambda < 2000$ Å, and to better than 2% for $\lambda < 20000$ Å. Oscillator strengths from the present calculation agree precisely with those given in Plante et al. (1995) for transitions between states with $n = 1$ and 2; they are also in close agreement (typically 0.01%) with values from Cann &

Thakkar (1992). Transition rates agree with the tabulated NIST values (Wiese et al. 1996) to better than 0.5% for $\lambda < 200$ Å, to better than 1% for $200 \leq \lambda < 2000$ Å, and to better than 2% for $\lambda < 20000$ Å.

Results of our calculations are given in Tables 1–12. Although we quote five significant figures for wavelengths and four significant figures for transition rates in these tables, the reader is cautioned that the accuracy of the wavelengths (and consequently the transition rates) as determined by the comparisons discussed above is substantially smaller for larger wavelengths. Length-form and velocity-form matrix elements for these transitions are in close agreement; however, there are small residual differences between length-form and velocity-form matrix elements caused by our neglect of contributions from negative-energy states. As discussed in Plante et al. (1995), these differences, when evaluated perturbatively, contribute only to velocity-form matrix elements, and bring velocity-form matrix elements into precise agreement with the corresponding length-form matrix elements. In the present tabulation, we list transition rates obtained from length-form calculations only.

In Tables 1–6, we present wavelengths and transition rates for singlet-singlet transitions of the type $(1snl) ^1L - (1sml') ^1L'$ with L and L' ranging through S, P, D, F . With the exception of the $n ^1P - m ^1S$ transitions listed in Table 1, $n - n$ transitions (which have wavelengths $\sim 10^5$ to 10^6 Å and transition rates $< 10^5$ s $^{-1}$) are omitted from the tables since *ab-initio* calculations for such cases are unreliable.

In Tables 7–10 we present wavelengths and transition rates for triplet-triplet transitions of the type $(1snl) ^3L - (1sml') ^3L'$ with L and L' ranging over S, P, D . In the astrophysical applications mentioned in the introduction, the fine-structure of the transitions is unresolved. We therefore average the triplet-triplet rates over individual fine-structure substates J_I, J_F . The average rates \bar{A} listed in the tables are given by

$$\bar{A} = \frac{\sum_{J_I, J_F} [J_F] A_{FI}}{3[L_F]}. \quad (14)$$

(Note that $3[L_F] = \sum_{J_F} [J_F]$ for triplet states.) Multiplet-average wavelengths $\bar{\lambda}$ are also listed in the tables. For reasons given in the previous para-

graph, we include $n - n$ transition data only for the $n ^3P - m ^3S$ transitions (Table 7).

The intercombination transitions between $n ^3P_1$ states and $m ^1S_0$ states, which are comparable in size to allowed transitions for highly-charged ions, are listed in Tables 11 & 12.

In summary, we present accurate wavelengths and transition rates for allowed singlet-singlet and triplet-triplet transitions and for intercombination transitions between triplet 3P_1 and singlet 1S_0 states with $n \leq 6$ in helium-like, carbon, nitrogen, oxygen, neon, silicon, and argon for use in the analysis of astrophysical plasmas.

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TABLE 1
WAVELENGTHS λ (Å) AND RADIATIVE TRANSITION RATES A (s^{-1}) FOR SINGLET-SINGLET TRANSITIONS
IN HE-LIKE IONS. NUMBERS IN BRACKETS REPRESENT POWERS OF 10.

Final Initial	1^1S_0		2^1S_0		3^1S_0		4^1S_0		5^1S_0	
	λ (Å)	A (s^{-1})	λ (Å)	A (s^{-1})	λ (Å)	A (s^{-1})	λ (Å)	A (s^{-1})	λ (Å)	A (s^{-1})
He-like carbon										
2^1P_1	40.266	8.862[11]	3524.7	1.672[07]						
3^1P_1	34.972	2.551[11]	247.31	1.277[10]	12160.	2.440[06]				
4^1P_1	33.426	1.064[11]	186.35	5.764[09]	711.69	1.663[09]	29083.	5.936[05]		
5^1P_1	32.754	5.420[10]	167.22	3.000[09]	495.34	9.318[08]	1543.0	3.897[08]	57105.	1.959[05]
6^1P_1	32.399	3.186[10]	158.36	1.780[09]	424.88	5.638[08]	1017.4	2.514[08]	2838.4	1.288[08]
He-like nitrogen										
2^1P_1	28.786	1.806[12]	2893.3	2.098[07]						
3^1P_1	24.900	5.149[11]	173.39	2.690[10]	9972.0	3.072[06]				
4^1P_1	23.771	2.141[11]	130.30	1.205[10]	498.19	3.531[09]	23835.	7.489[05]		
5^1P_1	23.281	1.089[11]	116.84	6.259[09]	345.82	1.965[09]	1079.5	8.316[08]	46755.	2.478[05]
6^1P_1	23.024	6.328[10]	110.62	3.667[09]	296.47	1.172[09]	710.40	5.268[08]	1989.4	2.721[08]
He-like oxygen										
2^1P_1	21.600	3.302[12]	2446.6	2.547[07]						
3^1P_1	18.627	9.344[11]	128.24	5.039[10]	8427.3	3.738[06]				
4^1P_1	17.767	3.876[11]	96.194	2.246[10]	368.10	6.654[09]	20139.	9.120[05]		
5^1P_1	17.395	1.970[11]	86.204	1.164[10]	255.01	3.683[09]	797.24	1.571[09]	39507.	3.018[05]
6^1P_1	17.199	1.146[11]	81.591	6.828[09]	218.48	2.198[09]	523.52	9.925[08]	1468.2	5.165[08]
He-like neon										
2^1P_1	13.446	8.853[12]	1852.6	3.542[07]						
3^1P_1	11.546	2.478[12]	78.251	1.397[11]	6375.9	5.214[06]				
4^1P_1	10.999	1.024[12]	58.547	6.182[10]	224.32	1.859[10]	15231.	1.274[06]		
5^1P_1	10.764	5.196[11]	52.427	3.194[10]	155.00	1.021[10]	485.61	4.405[09]	29849.	4.228[05]
6^1P_1	10.639	3.008[11]	49.607	1.864[10]	132.70	6.051[09]	318.10	2.752[09]	894.55	1.446[09]
He-like silicon										
2^1P_1	6.6466	3.757[13]	1195.5	6.276[07]						
3^1P_1	5.6796	1.037[13]	37.807	6.156[11]	4105.5	9.302[06]				
4^1P_1	5.4036	4.270[12]	28.214	2.703[11]	108.26	8.246[10]	9801.1	2.278[06]		
5^1P_1	5.2846	2.161[12]	25.246	1.392[11]	74.607	4.495[10]	234.26	1.961[10]	19189.	7.586[05]
6^1P_1	5.2221	1.244[12]	23.880	8.076[10]	63.822	2.644[10]	153.05	1.211[10]	431.60	6.426[09]
He-like argon										
2^1P_1	3.9478	1.071[14]	816.70	1.133[08]						
3^1P_1	3.3647	2.931[13]	22.162	1.790[12]	2793.9	1.697[07]				
4^1P_1	3.1989	1.203[13]	16.521	7.826[11]	63.436	2.402[11]	6661.5	4.173[06]		
5^1P_1	3.1275	6.078[12]	14.779	4.024[11]	43.669	1.305[11]	137.25	5.717[10]	13045.	1.389[06]
6^1P_1	3.0900	3.535[12]	13.976	2.358[11]	37.335	7.749[10]	89.522	3.557[10]	252.45	1.896[10]

TABLE 2
WAVELENGTHS λ (Å) AND RADIATIVE TRANSITION RATES A (s^{-1}) FOR SINGLET-SINGLET TRANSITIONS
IN HE-LIKE IONS. NUMBERS IN BRACKETS REPRESENT POWERS OF 10.

Final Initial	2^1P_1		3^1P_1		4^1P_1		5^1P_1	
	λ (Å)	A (s^{-1})	λ (Å)	A (s^{-1})	λ (Å)	A (s^{-1})	λ (Å)	A (s^{-1})
He-like carbon								
3^1S_0	271.92	5.707[09]						
4^1S_0	198.09	2.292[09]	776.10	1.565[09]				
5^1S_0	176.09	1.141[09]	521.09	7.539[08]	1677.3	5.361[08]		
6^1S_0	166.09	6.613[08]	442.23	4.272[08]	1065.6	2.954[08]	3079.7	2.234[08]
He-like nitrogen								
3^1S_0	187.92	1.127[10]						
4^1S_0	137.23	4.542[09]	536.18	3.110[09]				
5^1S_0	122.07	2.265[09]	361.01	1.505[09]	1158.7	1.070[09]		
6^1S_0	115.18	1.301[09]	306.71	8.458[08]	738.89	5.865[08]	2132.4	4.418[08]
He-like oxygen								
3^1S_0	137.55	2.013[10]						
4^1S_0	100.63	8.131[09]	392.41	5.583[09]				
5^1S_0	89.555	4.057[09]	264.73	2.708[09]	847.91	1.925[09]		
6^1S_0	84.510	2.336[09]	225.03	1.527[09]	541.73	1.060[09]	1559.5	7.983[08]
He-like neon								
3^1S_0	82.762	5.227[10]						
4^1S_0	60.698	2.117[10]	236.11	1.460[10]				
5^1S_0	54.052	1.057[10]	159.72	7.105[09]	510.17	5.052[09]		
6^1S_0	51.022	6.066[09]	135.88	3.995[09]	326.94	2.783[09]	938.91	2.094[09]
He-like silicon								
3^1S_0	39.416	2.149[11]						
4^1S_0	28.981	8.726[10]	112.47	6.054[10]				
5^1S_0	25.825	4.356[10]	76.290	2.954[10]	243.03	2.100[10]		
6^1S_0	24.385	2.490[10]	64.957	1.655[10]	156.22	1.157[10]	447.49	8.696[09]
He-like argon								
3^1S_0	22.967	6.071[11]						
4^1S_0	16.905	2.467[11]	65.549	1.715[11]				
5^1S_0	15.069	1.232[11]	44.514	8.380[10]	141.66	5.956[10]		
6^1S_0	14.229	7.123[10]	37.903	4.753[10]	91.101	3.323[10]	260.35	2.495[10]

TABLE 3
WAVELENGTHS λ (Å) AND RADIATIVE TRANSITION RATES A (s^{-1}) FOR SINGLET-SINGLET TRANSITIONS
IN HE-LIKE IONS. NUMBERS IN BRACKETS REPRESENT POWERS OF 10.

Final Initial	2^1P_1		3^1P_1		4^1P_1		5^1P_1	
	λ (Å)	A (s^{-1})	λ (Å)	A (s^{-1})	λ (Å)	A (s^{-1})	λ (Å)	A (s^{-1})
He-like carbon								
3^1D_2	267.28	3.930[10]						
4^1D_2	197.03	1.229[10]	760.16	4.410[09]				
5^1D_2	175.67	5.567[09]	517.36	2.096[09]	1639.3	9.415[08]		
6^1D_2	165.88	3.062[09]	440.75	1.169[09]	1057.1	5.468[08]	3009.5	2.905[08]
He-like nitrogen								
3^1D_2	185.22	8.137[10]						
4^1D_2	136.62	2.555[10]	526.87	9.117[09]				
5^1D_2	121.82	1.159[10]	358.81	4.344[09]	1136.4	1.944[09]		
6^1D_2	115.05	6.319[09]	305.80	2.401[09]	733.62	1.121[09]	2089.1	5.934[08]
He-like oxygen								
3^1D_2	135.83	1.501[11]						
4^1D_2	100.23	4.734[10]	386.47	1.682[10]				
5^1D_2	89.394	2.151[10]	263.33	8.033[09]	833.67	3.585[09]		
6^1D_2	84.429	1.176[10]	224.45	4.454[09]	538.42	2.075[09]	1532.3	1.096[09]
He-like neon								
3^1D_2	81.925	4.025[11]						
4^1D_2	60.504	1.284[11]	233.20	4.529[10]				
5^1D_2	53.972	5.853[10]	159.02	2.173[10]	503.17	9.658[09]		
6^1D_2	50.981	3.199[10]	135.59	1.205[10]	325.26	5.593[09]	925.25	2.945[09]
He-like silicon								
3^1D_2	39.098	1.628[12]						
4^1D_2	28.907	5.316[11]	111.37	1.860[11]				
5^1D_2	25.795	2.445[11]	76.026	9.014[10]	240.37	3.985[10]		
6^1D_2	24.369	1.339[11]	64.845	5.010[10]	155.57	2.318[10]	442.21	1.215[10]
He-like argon								
3^1D_2	22.791	4.502[12]						
4^1D_2	16.864	1.475[12]	64.938	5.142[11]				
5^1D_2	15.052	6.801[11]	44.368	2.501[11]	140.19	1.102[11]		
6^1D_2	14.220	3.761[11]	37.846	1.403[11]	90.770	6.481[10]	257.67	3.390[10]

TABLE 4
WAVELENGTHS λ (Å) AND RADIATIVE TRANSITION RATES A (s^{-1}) FOR SINGLET-SINGLET TRANSITIONS
IN HE-LIKE IONS. NUMBERS IN BRACKETS REPRESENT POWERS OF 10.

Final Initial	3^1D_2		4^1D_2		5^1D_2	
	λ (Å)	A (s^{-1})	λ (Å)	A (s^{-1})	λ (Å)	A (s^{-1})
He-like carbon						
4^1P_1	745.56	1.953[08]				
5^1P_1	511.51	8.443[07]	1610.1	1.077[08]		
6^1P_1	436.72	4.505[07]	1046.2	5.503[07]	2954.2	5.631[07]
He-like nitrogen						
4^1P_1	518.22	4.100[08]				
5^1P_1	355.35	1.773[08]	1119.3	2.263[08]		
6^1P_1	303.45	9.376[07]	727.44	1.145[08]	2058.9	1.170[08]
He-like oxygen						
4^1P_1	381.00	7.648[08]				
5^1P_1	261.14	3.306[08]	822.94	4.223[08]		
6^1P_1	222.96	1.752[08]	534.49	2.141[08]	1513.0	2.188[08]
He-like neon						
4^1P_1	230.72	2.085[09]				
5^1P_1	158.03	9.007[08]	498.38	1.158[09]		
6^1P_1	134.91	4.761[08]	323.53	5.851[08]	916.91	5.995[08]
He-like silicon						
4^1P_1	110.73	8.650[09]				
5^1P_1	75.772	3.734[09]	239.19	4.874[09]		
6^1P_1	64.673	1.967[09]	155.15	2.454[09]	440.25	2.530[09]
He-like argon						
4^1P_1	64.821	2.448[10]				
5^1P_1	44.321	1.057[10]	140.01	1.375[10]		
6^1P_1	37.811	5.621[09]	90.688	6.985[09]	257.25	7.201[09]

TABLE 5

WAVELENGTHS λ (Å) AND RADIATIVE TRANSITION RATES A (s^{-1}) FOR SINGLET-SINGLET TRANSITIONS IN HE-LIKE IONS. NUMBERS IN BRACKETS REPRESENT POWERS OF 10.

Final Initial	3^1D_2 λ (Å) A (s^{-1})	4^1D_2 λ (Å) A (s^{-1})	5^1D_2 λ (Å) A (s^{-1})
He-like carbon			
4^1F_3	749.60 6.005[09]		
5^1F_3	512.46 2.101[09]	1619.6 1.176[09]	
6^1F_3	437.25 1.026[09]	1049.2 6.061[08]	2978.7 3.391[08]
He-like nitrogen			
4^1F_3	520.61 1.255[10]		
5^1F_3	355.90 4.329[09]	1124.8 2.407[09]	
6^1F_3	303.70 2.089[09]	728.86 1.226[09]	2070.3 6.846[08]
He-like oxygen			
4^1F_3	382.50 2.377[10]		
5^1F_3	261.49 8.103[09]	826.41 4.477[09]	
6^1F_3	223.12 3.906[09]	535.46 2.278[09]	1520.8 1.269[09]
He-like neon			
4^1F_3	231.38 6.952[10]		
5^1F_3	158.18 2.333[10]	499.88 1.276[10]	
6^1F_3	134.98 1.115[10]	323.92 6.436[09]	920.05 3.569[09]
He-like silicon			
4^1F_3	110.88 3.441[11]		
5^1F_3	75.803 1.140[11]	239.51 6.276[10]	
6^1F_3	64.687 5.402[10]	155.22 3.138[10]	440.88 1.740[10]
He-like argon			
4^1F_3	64.821 1.066[12]		
5^1F_3	44.319 3.517[11]	140.00 1.972[11]	
6^1F_3	37.817 1.671[11]	90.721 9.884[10]	257.52 5.514[10]

TABLE 6

WAVELENGTHS λ (Å) AND RADIATIVE TRANSITION RATES A (s^{-1}) FOR SINGLET-SINGLET TRANSITIONS IN HE-LIKE IONS. NUMBERS IN BRACKETS REPRESENT POWERS OF 10.

Final	$4\ ^1F_2$		$5\ ^1F_3$	
Initial	λ (Å)	A (s^{-1})	λ (Å)	A (s^{-1})
He-like carbon				
$5\ ^1D_2$	1620.0	2.149[07]		
$6\ ^1D_2$	1049.0	9.238[06]	2976.6	1.794[07]
He-like nitrogen				
$5\ ^1D_2$	1125.0	4.449[07]		
$6\ ^1D_2$	728.87	1.893[07]	2070.1	3.623[07]
He-like oxygen				
$5\ ^1D_2$	826.54	8.348[07]		
$6\ ^1D_2$	535.44	3.553[07]	1520.4	6.723[07]
He-like neon				
$5\ ^1D_2$	500.03	2.411[08]		
$6\ ^1D_2$	323.95	1.022[08]	920.08	1.902[08]
He-like silicon				
$5\ ^1D_2$	239.70	1.207[09]		
$6\ ^1D_2$	155.29	5.101[08]	441.19	9.351[08]
He-like argon				
$5\ ^1D_2$	140.19	3.850[09]		
$6\ ^1D_2$	90.771	1.644[09]	257.71	3.000[09]

TABLE 7

AVERAGE WAVELENGTHS $\bar{\lambda}$ (Å) AND RADIATIVE TRANSITION RATES \bar{A} (s⁻¹) FOR TRIPLET-TRIPLET TRANSITIONS IN HE-LIKE IONS. NUMBERS IN BRACKETS REPRESENT POWERS OF 10.

Final Initial	2^3S		3^3S		4^3S		5^3S	
	$\bar{\lambda}$ (Å)	\bar{A} (s ⁻¹)	$\bar{\lambda}$ (Å)	\bar{A} (s ⁻¹)	$\bar{\lambda}$ (Å)	\bar{A} (s ⁻¹)	$\bar{\lambda}$ (Å)	\bar{A} (s ⁻¹)
He-like carbon								
2^3P	2272.3	5.695[07]						
3^3P	227.17	1.360[10]	8425.8	6.928[06]				
4^3P	173.26	6.187[09]	671.98	1.673[09]	20665.	1.586[06]		
5^3P	156.22	3.223[09]	472.13	9.483[08]	1474.3	3.821[08]	41075.	5.087[05]
6^3P	148.30	1.906[09]	406.54	5.738[08]	980.37	2.493[08]	2731.8	1.240[08]
He-like nitrogen								
2^3P	1899.1	6.865[07]						
3^3P	161.21	2.851[10]	7004.7	8.445[06]				
4^3P	122.42	1.285[10]	474.41	3.565[09]	17138.	1.943[06]		
5^3P	110.22	6.676[09]	331.95	2.001[09]	1038.5	8.214[08]	33998.	6.261[05]
6^3P	104.57	3.907[09]	285.51	1.196[09]	688.27	5.255[08]	1925.3	2.652[08]
He-like oxygen								
2^3P	1627.7	8.085[07]						
3^3P	120.32	5.315[10]	5979.5	1.003[07]				
4^3P	91.085	2.380[10]	352.73	6.726[09]	14605.	2.318[06]		
5^3P	81.916	1.234[10]	246.07	3.749[09]	770.85	1.559[09]	28950.	7.480[05]
6^3P	77.677	7.233[09]	211.42	2.239[09]	509.30	9.926[08]	1427.1	5.063[08]
He-like neon								
2^3P	1256.6	1.077[08]						
3^3P	74.350	1.462[11]	4588.0	1.354[07]				
4^3P	56.042	6.493[10]	216.83	1.880[10]	11179.	3.147[06]		
5^3P	50.328	3.356[10]	150.65	1.038[10]	472.77	4.389[09]	22119.	1.020[06]
6^3P	47.692	1.957[10]	129.27	6.156[09]	311.20	2.759[09]	874.56	1.428[09]
He-like silicon								
2^3P	833.99	1.790[08]						
3^3P	36.439	6.386[11]	3019.9	2.298[07]				
4^3P	27.340	2.812[11]	105.66	8.348[10]	7335.0	5.380[06]		
5^3P	24.515	1.449[11]	73.103	4.568[10]	229.82	1.964[10]	14486.	1.752[06]
6^3P	23.215	8.408[10]	62.637	2.690[10]	150.67	1.219[10]	424.68	6.401[09]
He-like argon								
2^3P	590.47	2.990[08]						
3^3P	21.530	1.862[12]	2123.9	3.911[07]				
4^3P	16.118	8.165[11]	62.242	2.453[11]	5146.8	9.216[06]		
5^3P	14.442	4.201[11]	43.087	1.337[11]	135.22	5.794[10]	10158.	3.006[06]
6^3P	13.670	2.462[11]	36.792	7.943[10]	88.436	3.617[10]	249.32	1.912[10]

TABLE 8
AVERAGE WAVELENGTHS $\bar{\lambda}$ (Å) AND RADIATIVE TRANSITION RATES \bar{A} (s⁻¹) FOR TRIPLET-TRIPLET
TRANSITIONS IN HE-LIKE IONS. NUMBERS IN BRACKETS REPRESENT POWERS OF 10.

Final Initial	2^3P		3^3P		4^3P		5^3P	
	$\bar{\lambda}$ (Å)	\bar{A} (s ⁻¹)	$\bar{\lambda}$ (Å)	\bar{A} (s ⁻¹)	$\bar{\lambda}$ (Å)	\bar{A} (s ⁻¹)	$\bar{\lambda}$ (Å)	\bar{A} (s ⁻¹)
He-like carbon								
3 ³ S	260.20	6.709[09]						
4 ³ S	189.29	2.607[09]	756.96	1.803[09]				
5 ³ S	168.44	1.279[09]	506.32	8.527[08]	1651.3	6.077[08]		
6 ³ S	159.01	7.324[08]	429.72	4.775[08]	1044.2	3.291[08]	3051.3	2.495[08]
He-like nitrogen								
3 ³ S	180.71	1.292[10]						
4 ³ S	131.87	5.057[09]	524.44	3.510[09]				
5 ³ S	117.41	2.488[09]	352.07	1.671[09]	1142.6	1.191[09]		
6 ³ S	110.87	1.416[09]	299.15	9.307[08]	725.85	6.441[08]	2113.7	4.867[08]
He-like oxygen								
3 ³ S	132.81	2.265[10]						
4 ³ S	97.125	8.917[09]	384.72	6.207[09]				
5 ³ S	86.515	4.395[09]	258.93	2.967[09]	837.34	2.114[09]		
6 ³ S	81.702	2.508[09]	220.12	1.659[09]	533.29	1.151[09]	1547.1	8.686[08]
He-like neon								
3 ³ S	80.410	5.742[10]						
4 ³ S	58.967	2.275[10]	232.31	1.590[10]				
5 ³ S	52.552	1.124[10]	156.87	7.647[09]	504.93	5.450[09]		
6 ³ S	49.637	6.407[09]	133.47	4.272[09]	322.80	2.974[09]	932.62	2.242[09]
He-like silicon								
3 ³ S	38.591	2.303[11]						
4 ³ S	28.376	9.200[10]	111.15	6.457[10]				
5 ³ S	25.302	4.558[10]	75.306	3.124[10]	241.20	2.226[10]		
6 ³ S	23.902	2.592[10]	64.127	1.742[10]	154.78	1.217[10]	445.25	9.168[09]
He-like argon								
3 ³ S	22.583	6.463[11]						
4 ³ S	16.624	2.591[11]	64.930	1.822[11]				
5 ³ S	14.825	1.286[11]	44.057	8.840[10]	140.79	6.297[10]		
6 ³ S	14.005	7.402[10]	37.519	4.991[10]	90.438	3.491[10]	259.31	2.627[10]

TABLE 9
AVERAGE WAVELENGTHS $\bar{\lambda}$ (Å) AND RADIATIVE TRANSITION RATES \bar{A} (s⁻¹) FOR TRIPLET-TRIPLET TRANSITIONS IN HE-LIKE IONS. NUMBERS IN BRACKETS REPRESENT POWERS OF 10.

Final Initial	2^3P		3^3P		4^3P		5^3P	
	$\bar{\lambda}$ (Å)	\bar{A} (s ⁻¹)	$\bar{\lambda}$ (Å)	\bar{A} (s ⁻¹)	$\bar{\lambda}$ (Å)	\bar{A} (s ⁻¹)	$\bar{\lambda}$ (Å)	\bar{A} (s ⁻¹)
He-like carbon								
3^3D	248.72	4.240[10]						
4^3D	186.72	1.412[10]	717.49	4.312[09]				
5^3D	167.40	6.554[09]	497.10	2.162[09]	1557.2	8.794[08]		
6^3D	158.48	3.650[09]	425.91	1.231[09]	1022.0	5.370[08]	2869.1	2.640[08]
He-like nitrogen								
3^3D	173.92	8.729[10]						
4^3D	130.35	2.892[10]	501.17	8.966[09]				
5^3D	116.80	1.340[10]	346.61	4.472[09]	1087.1	1.838[09]		
6^3D	110.56	7.387[09]	296.87	2.518[09]	712.56	1.106[09]	2004.8	5.476[08]
He-like oxygen								
3^3D	128.46	1.606[11]						
4^3D	96.148	5.304[10]	369.83	1.663[10]				
5^3D	86.121	2.454[10]	255.43	8.265[09]	801.82	3.422[09]		
6^3D	81.500	1.355[10]	218.67	4.657[09]	524.82	2.056[09]	1478.0	1.025[09]
He-like neon								
3^3D	78.294	4.328[11]						
4^3D	58.491	1.424[11]	225.09	4.538[10]				
5^3D	52.360	6.580[10]	155.17	2.244[10]	487.70	9.392[09]		
6^3D	49.538	3.622[10]	132.76	1.259[10]	318.65	5.599[09]	898.87	2.815[09]
He-like silicon								
3^3D	37.835	1.823[12]						
4^3D	28.206	5.994[11]	108.57	1.947[11]				
5^3D	25.233	2.768[11]	74.698	9.584[10]	235.08	4.058[10]		
6^3D	23.866	1.521[11]	63.871	5.361[10]	153.30	2.404[10]	433.20	1.219[10]
He-like argon								
3^3D	22.209	5.216[12]						
4^3D	16.539	1.708[12]	63.659	5.604[11]				
5^3D	14.791	7.877[11]	43.756	2.752[11]	137.77	1.172[11]		
6^3D	13.987	4.358[11]	37.397	1.549[11]	89.728	6.979[10]	253.57	3.556[10]

TABLE 10
AVERAGE WAVELENGTHS $\bar{\lambda}$ (Å) AND RADIATIVE TRANSITION RATES \bar{A} (s⁻¹) FOR TRIPLET-TRIPLET
TRANSITIONS IN HE-LIKE IONS. NUMBERS IN BRACKETS REPRESENT POWERS OF 10.

Final Initial	3^3D		4^3D		5^3D	
	$\bar{\lambda}$ (Å)	\bar{A} (s ⁻¹)	$\bar{\lambda}$ (Å)	\bar{A} (s ⁻¹)	$\bar{\lambda}$ (Å)	\bar{A} (s ⁻¹)
He-like carbon						
4^3P	762.96	2.928[08]				
5^3P	515.31	1.248[08]	1651.1	1.530[08]		
6^3P	438.15	6.627[07]	1055.6	7.679[07]	3035.4	7.732[07]
He-like nitrogen						
4^3P	528.55	5.841[08]				
5^3P	357.58	2.495[08]	1143.6	3.069[08]		
6^3P	304.27	1.313[08]	732.93	1.531[08]	2106.8	1.543[08]
He-like oxygen						
4^3P	387.61	1.049[09]				
5^3P	262.56	4.486[08]	838.50	5.537[08]		
6^3P	223.47	2.367[08]	537.98	2.770[08]	1543.6	2.795[08]
He-like neon						
4^3P	233.88	2.734[09]				
5^3P	158.69	1.170[09]	505.81	1.454[09]		
6^3P	135.14	6.155[08]	325.18	7.260[08]	931.55	7.350[08]
He-like silicon						
4^3P	111.78	1.112[10]				
5^3P	75.981	4.765[09]	241.66	5.979[09]		
6^3P	64.738	2.499[09]	155.67	2.981[09]	445.11	3.031[09]
He-like argon						
4^3P	65.268	3.139[10]				
5^3P	44.400	1.346[10]	141.08	1.691[10]		
6^3P	37.829	7.135[09]	90.907	8.522[09]	259.41	8.671[09]

TABLE 11

WAVELENGTHS λ (Å) AND RADIATIVE TRANSITION RATES A (s^{-1}) FOR TRIPLET-SINGLET TRANSITIONS IN HE-LIKE IONS. NUMBERS IN BRACKETS REPRESENT POWERS OF 10.

Final Initial	1^1S_0		2^1S_0		3^1S_0		4^1S_0		5^1S_0	
	λ (Å)	A (s^{-1})	λ (Å)	A (s^{-1})	λ (Å)	A (s^{-1})	λ (Å)	A (s^{-1})	λ (Å)	A (s^{-1})
He-like carbon										
2^3P_1	40.751	2.696[07]								
3^3P_1	35.086	7.831[06]	252.41	4.524[05]						
4^3P_1	33.477	3.289[06]	187.57	1.985[05]	729.09	6.230[04]				
5^3P_1	32.786	1.699[06]	167.75	1.035[05]	499.63	3.397[04]	1584.5	1.517[04]		
6^3P_1	32.423	1.086[06]	158.68	6.608[04]	426.92	2.187[04]	1028.8	1.014[04]	2927.8	5.502[03]
He-like nitrogen										
2^3P_1	29.095	1.346[08]								
3^3P_1	24.970	3.984[07]	176.50	2.357[06]						
4^3P_1	23.802	1.684[07]	131.04	1.041[06]	508.76	3.279[05]				
5^3P_1	23.301	8.669[06]	117.15	5.415[05]	348.40	1.783[05]	1104.6	7.979[04]		
6^3P_1	23.038	5.292[06]	110.80	3.312[05]	297.61	1.100[05]	716.78	5.108[04]	2039.8	2.775[04]
He-like oxygen										
2^3P_1	21.810	5.352[08]								
3^3P_1	18.674	1.605[08]	130.28	9.667[06]						
4^3P_1	17.788	6.811[07]	96.676	4.290[06]	374.99	1.354[06]				
5^3P_1	17.407	3.506[07]	86.409	2.231[06]	256.69	7.360[05]	813.60	3.298[05]		
6^3P_1	17.208	2.093[07]	81.710	1.337[06]	219.24	4.451[05]	527.78	2.068[05]	1501.8	1.124[05]
He-like neon										
2^3P_1	13.555	5.253[09]								
3^3P_1	11.570	1.604[09]	79.265	9.896[07]						
4^3P_1	11.010	6.840[08]	58.785	4.421[07]	227.74	1.399[07]				
5^3P_1	10.769	3.523[08]	52.528	2.303[07]	155.83	7.608[06]	493.68	3.414[06]		
6^3P_1	10.644	2.067[08]	49.664	1.357[07]	133.06	4.526[06]	320.14	2.105[06]	910.80	1.145[06]
He-like silicon										
2^3P_1	6.6878	1.550[11]								
3^3P_1	5.6884	4.798[10]	38.172	3.047[09]						
4^3P_1	5.4073	2.054[10]	28.299	1.369[09]	109.49	4.337[08]				
5^3P_1	5.2867	1.059[10]	25.282	7.145[08]	74.902	2.364[08]	237.15	1.061[08]		
6^3P_1	5.2236	6.161[09]	23.900	4.179[08]	63.950	1.396[08]	153.77	6.498[07]	437.31	3.536[07]
He-like argon										
2^3P_1	3.9685	1.782[12]								
3^3P_1	3.3691	5.486[11]	22.341	3.548[10]						
4^3P_1	3.2007	2.343[11]	16.563	1.593[10]	64.040	5.046[09]				
5^3P_1	3.1285	1.206[11]	14.796	8.305[09]	43.814	2.748[09]	138.68	1.234[09]		
6^3P_1	3.0907	7.001[10]	13.987	4.848[09]	37.408	1.620[09]	89.929	7.542[08]	255.70	1.620[09]

TABLE 12

WAVELENGTHS λ (Å) AND RADIATIVE TRANSITION RATES A (s^{-1}) FOR SINGLET-TRIPLET TRANSITIONS IN HE-LIKE IONS. NUMBERS IN BRACKETS REPRESENT POWERS OF 10.

Final Initial	2^3P_1 λ (Å) A (s^{-1})	3^3P_1 λ (Å) A (s^{-1})	4^3P_1 λ (Å) A (s^{-1})	5^3P_1 λ (Å) A (s^{-1})
He-like carbon				
3^1S_0	252.51 1.209[05]			
4^1S_0	187.60 4.961[04]	730.80 3.665[04]		
5^1S_0	167.76 2.484[04]	500.31 1.803[04]	1589.25 1.313[04]	
6^1S_0	158.68 1.418[04]	427.37 1.010[04]	1030.55 7.273[03]	2937.4 5.558[03]
He-like nitrogen				
3^1S_0	176.14 6.094[05]			
4^1S_0	130.85 2.502[05]	508.97 1.898[05]		
5^1S_0	117.00 1.253[05]	348.48 9.349[04]	1105.9 6.858[04]	
6^1S_0	110.66 7.156[04]	297.66 5.239[04]	717.26 3.803[04]	2042.9 2.900[04]
He-like oxygen				
3^1S_0	129.87 2.446[06]			
4^1S_0	96.463 1.005[06]	374.80 7.768[05]		
5^1S_0	86.240 5.033[05]	256.61 3.828[05]	813.84 2.823[05]	
6^1S_0	81.558 2.874[05]	219.17 2.145[05]	527.87 1.566[05]	1502.8 1.194[05]
He-like neon				
3^1S_0	78.964 2.442[07]			
4^1S_0	58.632 1.003[07]	227.482 7.953[06]		
5^1S_0	52.407 5.025[06]	155.721 3.920[06]	493.51 2.911[06]	
6^1S_0	49.556 2.870[06]	132.991 2.198[06]	320.08 1.616[06]	910.78 1.234[06]
He-like silicon				
3^1S_0	38.058 7.402[08]			
4^1S_0	28.241 3.037[08]	109.41 2.461[08]		
5^1S_0	25.236 1.521[08]	74.869 1.213[08]	237.13 9.057[07]	
6^1S_0	23.859 8.682[07]	63.926 6.800[07]	153.76 5.028[07]	437.40 3.845[07]
He-like argon				
3^1S_0	22.304 8.679[09]			
4^1S_0	16.543 3.557[09]	64.050 2.881[09]		
5^1S_0	14.781 1.780[09]	43.818 1.420[09]	138.77 1.058[09]	
6^1S_0	13.973 1.016[09]	37.409 7.957[08]	89.963 5.875[08]	255.92 4.488[08]

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